

AD-A043 542

ROCHESTER UNIV N Y LAB FOR LASER ENERGETICS

SOFT X-RAY AMPLIFICATION IN A LASER-PRODUCED PLASMA: A REVIEW

JUL 75 J M FORSYTH, T C BRISTOW, B YAAKOB

F/G 20/5

A--ETC(U)

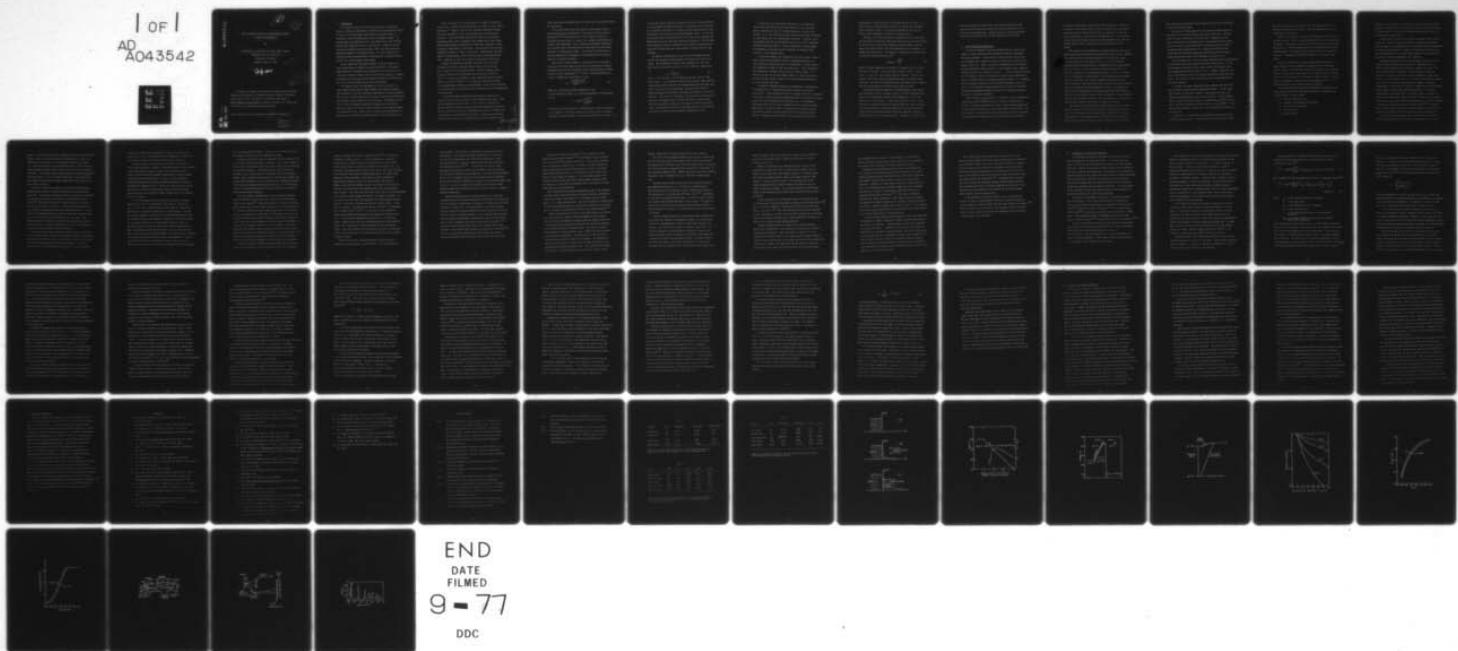
N00014-67-A-0398-0017

NL

UNCLASSIFIED

| OF |  
AD  
A043542

REF



END

DATE

FILMED

9 - 77

DDC

ADA043542

(6) SOFT X-RAY AMPLIFICATION IN A LASER-PRODUCED PLASMA:  
A REVIEW AND PROGNOSIS

by

(10) J.M. Forsyth, T.C. Bristow, B. Yaakobi, and A. Hauer

Laboratory for Laser Energetics ✓

University of Rochester

Rochester, New York 14627

(12) 58P.

D D C

RECORDED  
AUG 30 1977  
RESULTS  
GT A

(11) July 1975

This paper is a summary of a tutorial talk presented to the seventh conference on The Physics of Quantum Electronics, Sante Fe, New Mexico, June 23-July 4, 1975. The paper is submitted for publication in Recent Advances in Laser Physics, edited by M. Sargent, M.O. Scully, and W.E. Lamb, Jr., to be published by Addison Wesley.

\* Work supported in part by ARPA Contract N00014-67-A-0398-0017

AU NO.  
DOC FILE COPY

DISTRIBUTION STATEMENT A  
Approved for public release;  
Distribution Unlimited

409 612

## I. INTRODUCTION

The reader of volume 3 of this series will have a considerable wealth of information immediately available on the very important subject of the use of high peak power laser pulses to heat plasma media to temperatures favoring thermonuclear fusion of hydrogen isotopes. In plasmas where such temperatures exist the conditions may also exist for the efficient production of soft x-ray radiation. Efforts to utilize radiation so produced to optically pump a soft x-ray laser system are described elsewhere in the present volume. It is the intent of this article to discuss the prospects for observing soft x-ray amplification directly in a laser-produced plasma medium.

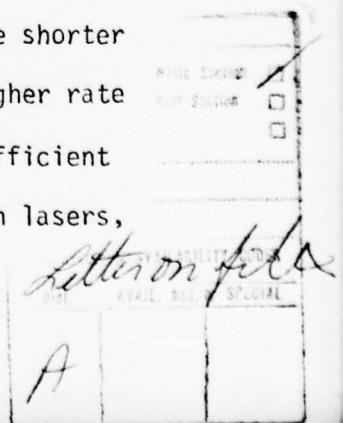
We will begin with some general remarks on the suitability of a laser heated plasma to produce an amplifying condition. The several mechanisms which can produce x-ray excited states in a plasma will be listed with particular emphasis given to collisional processes. Examples of proposals for achieving inverted populations which rely primarily on one of each of these mechanisms will then be presented.

The number of ideas for development of a soft x-ray laser in a laser produced plasma seems endless; however, most ideas are based on the assumption of a certain convenient, detailed set of plasma conditions. The existence of these conditions has not been experimentally demonstrated (or refuted) in most instances as of this writing. Accordingly, we will discuss efforts to deduce the detailed information on laser plasma parameters required to choose the most promising of the proposed schemes for experimental test. Finally, we will discuss some considerations in the design of an experiment to observe gain in a laser produced plasma.

There is no doubt that a plasma medium is suitable for producing laser action: electric gas discharge lasers are almost as old as lasers themselves.<sup>(1)</sup> However, there are some important differences between the plasma conditions in, say, a helium-neon laser and laser-plasma conditions. These differences have made it difficult to extend and extrapolate known electric discharge laser schemes using laser plasmas. Laser produced plasmas are typically of rather small dimensions, often occupying a volume  $100\mu\text{m}$  or less across. Gas discharge lasers may have dimensions of meters or larger in some cases. Interestingly, the total number of excited atoms or ions in the two cases is approximately the same. Therefore, we must look further for the source of difficulty.

Perhaps the single most important difference lies in the vast difference in particle densities present in gas lasers versus the active region of a laser produced plasma. Electric discharge lasers typically operate with electron densities in the range of  $10^{11}$  to  $10^{13}\text{cm}^{-3}$  while the active regions in laser plasmas may exhibit electron densities of  $10^{17}$  to  $10^{21}\text{cm}^{-3}$ . It is clear that collision processes will be emphasized differently in the two media. A part of the difference in collision effects arises from the vast difference in particle temperature in the two cases.

At short wavelengths high particle densities are necessary for achieving laser action on all but strictly forbidden transitions. There are two important reasons for this. First, since the lifetimes of excited states for allowed x-ray and extreme VUV transitions are shorter than for transitions at optical wavelengths (see Table 1), a higher rate of production of excited states is required. Secondly, since efficient optical cavities have not yet been designed for short wavelength lasers,



rather high inversion densities will be required just to produce evidence of laser action.

It has been predicted for some time that laser plasma electron densities were more than adequate for very rapid x-ray excited state production.<sup>(2,3)</sup> The difficulty is to find systems in which this excitation does not result in a normal (i.e., thermal) distribution of excited state populations. This last point may be better appreciated if we consider some of the characteristic time scales for collisional processes in a high density plasma. A time scale of interest here is the time required for an ensemble of colliding particles to develop a Maxwellian velocity distribution.

The classical kinetic theory of a plasma allows us to consider a situation in which the electrons and ions in the plasma have slightly non-Maxwellian velocity distributions and are characterized by slightly different kinetic temperatures.<sup>(4)</sup> In such a case the electrons will relax to a Maxwellian distribution in a time

$$\tau_{ee} = \frac{3.32 \times 10^5 (kT_e)^{3/2}}{n_e \ln \Lambda} \quad (1)$$

where  $kT_e$  is the plasma electron temperature in eV,  $e$  is the electronic charge,  $n_e$  is the electron density in particles per  $\text{cm}^3$  and

$$\Lambda = 1.87 \times 10^6 \frac{(kT_e)^{3/2}}{(\pi n_e e^6)^{1/2}}$$

A Maxwellian distribution will be achieved only if inelastic collisions can be neglected. Of course, the key to exciting a laser is to take advantage of certain inelastic collisions with large cross sections. As

a result the electron velocity distribution is never strictly Maxwellian in a collisionally excited laser system. In most such lasers the effect of the inelastic collisions is to quench the high energy spectrum of the distribution while leaving the low energy spectrum intact. In this case the electron velocity distribution will still relax to its approximately Maxwellian form on the time scale indicated in equation 1. We will take this estimate as a guide in analyzing a laser plasma, recognizing that inelastic collisions may play a more important role here than in a gas discharge.

An important consideration arises for laser development when we consider the exchange of energy between the electrons and ions in the plasma. The characteristic time for such exchange (i.e., the time required for the electrons and ions to come to identical temperatures) is

$$\tau_{e-i} = \frac{M}{m} \frac{1}{z^2} \tau_{e-e} \quad (2)$$

where M is the ion mass, m is the electron rest mass, and ze is the ionic charge. In a low density plasma this time can be longer than the characteristic time for the ions to exchange energy with some heat sink such as the walls of a discharge tube. Thus the ion and electron temperatures may be maintained at substantially different values at low densities. This results in high gain on inverted transitions because of relatively low Doppler widths. On the other hand, at high particle densities the principal coupling of the ions is to the plasma electron cloud. At high densities we must be concerned about the time scale for significant ion heating and the potential degradation of gain.

In Table 2 we list some plasma conditions in a few common gas lasers along with typical laser plasma conditions. The time scales given by equations (1) and (2) in these plasmas are listed for comparison. It is clear that we can expect to avoid significant ion heating in laser plasmas only on a subnanosecond time scale. Moreover, if we have produced hot ions we must expect to wait for at least a nanosecond to obtain significant cooling. Further significance to these numbers will develop as we consider specific proposals for producing laser action in a laser produced plasma.

In Table 3 we compare the linewidths of the laser systems listed in Table 2 with calculated Doppler widths on representative soft x-ray transitions which could be excited in a laser plasma. We have chosen an ion temperature of 200eV for the laser plasma ions. Such a temperature may characterize the higher density regions of such a plasma. It is worth noting that the relative Doppler widths in a laser plasma may be no worse than the relative width of the collision-broadened transition in a hgh pressure CO<sub>2</sub> laser.

In addition to Doppler broadening a contribution to the broadening of spectral lines in a high density plasma arises due to collision processes.<sup>(5)</sup> Since charged particles are involved, each ion is subjected to the electric field produced by neighboring particles (electrons or ions), leading to a Stark broadening of the spectral line. The broadening contribution from ions is usually treated by the so-called quasi-static approximation in which the ratio of average particle speed to average interparticle distance is small compared to the line profile width of interest. Broadening from electrons is usually treated by the impact

approximation in which the above ratio exceeds the profile width. In either case the Stark width may be equal to or greater than the Doppler widths referred to above. Since particle proximities increase with density, Stark broadening is important at high densities.

Perhaps a more important process in degrading inverted populations are non-radiative transitions induced by inelastic electron-ion collisions. If this collision time is short compared to radiative decay times (or other level pumping times), then level populations will be sustained at thermal equilibrium values. An estimate of the inelastic collision time is given for allowed transitions as<sup>(5)</sup>

$$\tau_{\text{inelastic}} = \frac{10^6 Z^3}{n_e} \quad (3)$$

where the plasma temperature is assumed to be appropriate for exciting the lines of interest. For the gas lasers listed in Table 1, these times are longer than the relevant radiative lifetimes. For the laser plasmas listed these times are approximately equal to resonance level lifetimes. The choice of plasma density and ion charge state is clearly crucial to the success of any laser plasma inversion scheme.

Having emphasized the important differences between laser plasmas and conventional electric discharge lasers it is worth remembering that none of these differences precludes the achievement of a population inversion in a laser plasma. It does point up the fact that if we are to realize a practical level of gain that we need to be very successful in taking advantage of a selective mechanism for excitation because of large transition linewidths and the short time required to establish thermal equilibrium in high density media. In the next section we will

review the process of production of a high density plasma by a high power pulse of focussed laser energy and discuss the mechanisms for x-ray excited state production. Proposed schemes for producing inverted populations which rely on each of these mechanisms will be given.

## II. X-RAY EXCITED STATE PRODUCTION

It would be desirable to discuss the production of x-ray excited states in a laser plasma from the standpoint of detailed knowledge of the plasma parameters. Unfortunately, at this writing we do not have such knowledge and it appears that years of intensive research are still needed in this area. Much of our present understanding of the subject has been supplied by research efforts in laser induced fusion, extensive summaries of which are included in volume 3. For our present discussion it will suffice to rely on a simple model of laser plasma conditions in order to introduce many of the proposed inversion schemes. It is probably fair to say that a major goal in the ultimate development of an x-ray laser is to learn how real plasma conditions will affect the viability of the various proposed schemes and to use this information to design a successful x-ray laser experiment.

When infrared or optical energy is incident on a solid surface with intensities of  $10^{11}$ - $10^{12}$  W/cm<sup>2</sup> or more, a plasma is formed near the surface. At these field intensities free or weakly bound electrons will be accelerated significantly by the intense optical electric field. For our purposes it does not matter whether these free electrons are present due to impurities or due to various ionization processes (including

multiphoton ionization) excited by the incident laser beam. Under the influence of such intense optical fields the free electrons can acquire sufficient energy to ionize neutral atoms or molecules at or near the solid surfaces over a time span of a few optical cycles. The resulting cascade ionization rapidly increases the free electron density near the surface which, in turn, increases the rate of absorption of laser energy.

The details of the development of the plasma during the very early phases have not been extracted from experiments at this writing. However, it is sufficient for our present discussion to visualize the plasma development along the lines shown in Fig. 1. In Fig. 1a we show a particle density distribution,  $N(x)$ , representing a solid, plane surface at the point  $x=0$ . In Fig. 1b some ionization near the surface has occurred, probably on a subpicosecond time scale. In Fig. 1c a plasma density distribution has developed which may become approximately stable in shape (though not fixed in space) depending on the time scale of laser irradiation. The electrons in this plasma can execute oscillations under the influence of plasma electrostatic forces. The frequency of oscillation is proportional to the square root of the particle density. Where the electron density reaches a level (called the "critical" density) such that the electrons oscillate at the same frequency as the applied optical field, incident laser energy is stored in the medium.

The damping of these oscillations excites many processes including particle heating, fast particle acceleration, back scattered radiation at the laser frequency and various harmonics, and radiation of x-rays. As absorption of laser energy continues the particle temperatures are determined by a balance between the rate of delivery of laser energy,

heat conduction by the plasma into the target and the relative importance of the other processes above.

The balance of energy among the various plasma processes depends on many factors such as laser intensity and target composition. The time scale for laser irradiation is also important. Although short time scale irradiation may not optimize total x-ray production by the plasma, it is most likely to avoid significant ion heating (eq.2) and achieve non-thermal level populations (eq.3). Ignoring some details we may picture the plasma electron temperature and density profiles at some instant during short pulse laser irradiation as shown in Fig. 2.

We have divided Fig. 2 into four regions along the abscissa corresponding to various positions with respect to the laser target surface. It may be convenient to visualize a plane target surface with incident laser energy approaching from the right of Fig. 2. Region I represents the solid target material which is not heated significantly during the laser pulse. The electrons in this region may be free or bound depending on the target material.

In region II we show a steeply decreasing electron density profile and a rapidly increasing electron temperature profile. In this region the electrons and ions form a plasma. Heat conductivity keeps the temperature high through the outer zone of region II. With a neodymium laser ( $\lambda=1.06\mu$ ) the critical density is approximately  $n_e=10^{21}\text{cm}^{-3}$  while with a  $\text{CO}_2$  laser ( $\lambda=10.6\mu$ ) the critical density is at  $n_e=10^{19}\text{cm}^{-3}$ . Thus the profiles indicated in figure 1 will look quantitatively different in the two cases.

Region III is a low density, high temperature region which can be called the coronal region. The absorption of laser energy is not high

here but the primary loss mechanism is due to expansion which is not effective on very short time scales. Thus the temperature tends to be rather high in this region.

Region IV is an area of essentially free expansion if the target is located in vacuum. There is a negligible absorption of laser energy and the density is becoming so low that collisions become infrequent between the particles. Thus the thermal velocities possessed by particles near the outer edge of the corona become directed velocities of expansion in region IV. Consequently, the kinetic temperature is reduced in this region.

While it is difficult to ascribe sharply defined boundaries to these regions, we can give approximate dimensions to the important central regions. Typically under high power focussed laser irradiation region II will be from a few microns to a few tens of microns in extent while region III may be up to a millimeter or more in extent. In fact, precise measurements of the actual profiles suggested by Fig. 2 is a challenging area of laser plasma diagnostics research.

Having established an approximate environmental framework for our discussion we can list five important mechanisms for producing x-ray excited states in a laser plasma,

- 1) electron impact collisions
- 2) radiative and three-body recombination
- 3) dielectronic recombination
- 4) photoexcitation
- 5) charge exchange.

Proposals involving each of these mechanisms have been given to produce population inversions in a laser plasma. Before considering the specifics of such proposals it may be worth connecting these processes with the various regions given in Fig. 2.

Electron impact processes are important throughout most of regions II and III. Because of the wide variation of temperature and density over the region, such processes may offer the widest range of opportunities for excited state production. However, if laser plasma conditions are fairly represented in Fig. 2, then the most energetic x-ray states will be excited in the high temperature area, region II.

Recombination processes also occur throughout regions II and III. However, high-lying bound levels produced in recombination may be collisionally destroyed before significant radiation can occur. Collisional destruction is suppressed at lower densities so that the formation of radiating, energetic states by recombination tends to be favored in the outer edge of region III. Not all recombination processes are favorable to inverting level populations, however. Radiative recombination, in particular, is favored to energy levels of low principal quantum number thus precluding inverted populations. Three body recombination, on the other hand, is favored to levels of higher principal quantum number which should favor the achievement of an inversion. The conditions under which three body recombination may dominate radiative recombination have been discussed in several places.<sup>(6,7)</sup> It appears that the outer zones of region III may provide the desired conditions at least over a portion of the time history of the laser heating pulse.

In addition to the above processes, dielectronic recombination is also an important mechanism for excited state production in a laser

plasma. In this process the kinetic energy of an initially free electron appears, in part, as orbital energy on recombination and, in part, as additional orbital energy to an already bound electron in the plasma ion. The resulting ion is said to be doubly excited. There are several modes of decay for doubly excited levels, some of which may be strongly radiative. Use of these levels has been proposed in possible population inversion schemes. In a laser plasma, dielectronic capture should be most favored in high density, moderate temperature regions such as the inner zone of region II.

Since laser plasmas are strong x-ray emitters, one would expect photoexcitation to make a significant contribution to excited state production. In particular, radiation trapping is thought to be important in accounting for details in the observed line spectrum from laser plasmas.<sup>(8)</sup> Because trapping effects increase with ion density they should be most important in region II. However, radiation produced in, say, region II may penetrate to the solid substrate, region I. In such a case direct photoionization of inner shell electrons is possible with the resultant emission of characteristic (e.g., K <sub>$\alpha$</sub> ) x-rays. Such photoexcitation is discussed as a mechanism for population inversion in a companion article. However, photoexcitation in the plasma medium has also been proposed to produce inverted populations.

As the hot plasma expands the particle density becomes low and the initial thermal energy is converted into energy of expansion. Neglecting fast particles produced by strong, local electric fields near the target surface, the expanding plasma is electrically neutral. Thus, even though the bulk of the thermal energy may have been possessed by the

electrons, virtually the entire expansion energy is possessed by the massive ions. For a 1 keV (typical) electron temperature in region III, ion expansion energies of 10 keV or more are found in region IV.

Ordinarily region IV represents a transition to hard vacuum in laser plasma experiments. However, it has been proposed that by supplying a weak background gas around the target that the expanding ions in region IV may have sufficient energy to participate in charge exchange collisions with the background gas. The use of charge exchange to selectively populate excited states and obtain population inversion is discussed in a companion article. The use of a laser plasma as the ion source may be a practical alternative to the use of particle beams, especially since large currents of highly stripped ions can be produced from a laser plasma.

We will now review some of the proposals for producing inverted populations on soft x-ray transitions in the ions of a laser heated plasma. While some of these schemes have been subject to experimental investigation, a systematic study of even a limited number of them has not yet been completed. Because of this, even some preliminary results of a negative nature cannot be taken as indicative of the ultimate worth of a particular scheme; nor can some positive results be taken for guidance because of the limited value of the evidence gathered so far. Many of the proposed schemes involve the use of a very high peak power, short pulse laser to heat the plasma medium. Such lasers require expensive and sophisticated facilities found in only a few laboratories. Some of the available facilities are dedicated, at least in part, to other research efforts such as laser fusion, thus further limiting the possible

size of the experimental program. Clearly it will be some time before the schemes discussed here can be thoroughly explored.

Among the most fertile areas for suggested inversion schemes is the use of direct electron collisional excitation. This is true in spite of the fact that few existing lasers rely on this method alone for selective excited state production. (Of these, moreover, some have no x-ray analogue, such as the excitation of vibrational levels of molecules.) However, direct electron impact excitation is the dominant mechanism for excited state production in a laser plasma and will probably be the key first step in any pumping scheme within the plasma. To illustrate the variety of possible approaches with direct excitation we will briefly review two contrasting proposals.

One early proposal suggested that a self-terminating inversion might be achieved in helium-like ions of elements of moderate atomic weight such as oxygen.<sup>(9)</sup> A two step process was proposed in which one laser pulse would be used to create a plasma with an adequate density of  $O^{+6}$  ions and a second pulse would produce rapid heating of the plasma electrons, preferably on a time scale of  $10^{-12}$  seconds (see eq. 3). For  $T_e \sim 1\text{kev}$  preferential excitation of 3p levels should occur relative to the 2s levels for a few picoseconds, inverting the  $3p \rightarrow 2s$  transition. A diagram of this scheme is shown in Fig. 3. Ultimately, the 2s level population will normalize due to radiative relaxation from the 3p and higher levels and due to collisional relaxation from the 2p levels. The peak gain which might be expected will depend on the extent to which direct excitation of the forbidden  $1s \rightarrow 2s$  transitions may be neglected.

Direct excitation of optically forbidden transitions by electron impact is quite probable in some cases and has itself been proposed as

a path to an upper laser level in carbon-like ions.<sup>(10)</sup> A diagram of the scheme is shown in Fig. 4. In this configuration an inversion is achieved due to a great difference in the decay ratio of the excited states rather than in a significant difference in excitation rates. In particular, the rapid radiative decay rate of the 3s lower level compared to the 3p upper level makes the scheme potentially cw if stable plasma conditions could be attained. This would be a great advantage for experimental diagnosis as well as for many possible applications. However, there are some drawbacks as well, due chiefly to the fact that the laser transition would occur between levels of the same principal quantum number. This means that the system scales slowly to short wavelengths as a function of atomic number and implies a low quantum efficiency. It also means that one cannot take advantage of very high electron densities because of collisional relaxation between the 3p and 3s levels. In the published proposal a maximum electron density of  $10^{17} \text{ cm}^{-3}$  is recommended for the carbon-like  $O^{+2}$  ion.<sup>(10)</sup> If a Nd laser is used to heat the plasma such an electron density may not be realized until region IV in Fig. 2. This would be undesirable because this is a collisionless regime. However, with a CO<sub>2</sub> laser this electron density might appear in region III or even region II and the prospects for success might be higher. Very little attention has been given to matching the wavelength of the laser heating pulse to the desired plasma conditions in published proposals to date.

Proposals for using a recombining plasma to achieve inverted populations have been given by several authors. The common feature of

these proposals is the concept of subjecting a high density plasma to rapid cooling. This permits three-body recombination to predominate over radiative recombination thus favoring the population of higher lying quantum levels. Details of such processes have been calculated for hydrogen-like ions.<sup>(6,7,11)</sup> In some cases the initial plasma temperature and density are taken a priori without a detailed proposal for achieving the desired initial conditions. For laser plasma experiments this is still acceptable since we do not yet have detailed information of the time histories of temperatures and densities represented schematically in Fig. 2. At the very least the calculations yield certain minimum conditions which must eventually be found in order to achieve an inversion through recombination.

Inversions produced under the assumed conditions are inevitably transient because of the eventual expansion of the plasma to low densities (favoring radiative recombination) and because of radiative and collisional relaxation to lower levels. The time scales for the latter processes are much faster than the plasma expansion time and represent the limiting duration time for a possible inversion. In low Z plasmas the relaxation times are typically picoseconds; inversions have been calculated to the ground state of hydrogenic ions which are even shorter than this.<sup>(11)</sup> Inversions between excited levels appear to be somewhat longer lived, although of lower density than inversions on ground state transitions.<sup>(12)</sup> Of course, ground state transitions are more energetic and yield a substantially higher quantum efficiency than excited state transitions.

Evidence of inverted populations in  $C^{+5}$  in a recombining, laser produced plasma has been reported.<sup>(13)</sup> The estimated inversion density was too low ( $10^{11} \text{ cm}^{-3}$ ) to provide useful gain. If the general character of the distributions shown in Fig. 2 is correct, then the required low plasma temperatures to favor recombination will be found in the outer corona where densities are low. If inversions can be achieved at all, they are likely to be of low density. All such schemes appear to be limited to excited state transitions because thermal conduction times are longer, as a rule, than the relaxation time of inversions on ground state transitions discussed above.

While radiative and three body recombinations lead to the formation of excited states accessible by means of direct collisions, dielectronic recombination leads to the formation of a different class of excited states, i.e., doubly excited states. The use of dielectronic recombination to achieve inverted populations on extreme VUV transitions is one of the earliest proposals for obtaining gain from a laser produced plasma.<sup>(14)</sup>

Doubly excited levels are states of very high energy for an atom or ion; they usually lie above the ionization energy for one electron. Thus one of the most important relaxation paths for doubly excited ions is the ejection of one excited electron with the simultaneous reduction of the second electron to the ground state. This process is called autoionization, or the Auger effect, and is clearly the inverse process to dielectronic recombination. In addition, one of the two excited electrons may relax with the emission of a photon. The probability of this type of relaxation is usually much lower than the probability of autoionization, but grows strongly with  $z$ . Line radiation from doubly excited states is sometimes quite strong from laser produced plasmas

because a high density of doubly excited ions is often achieved.

The spectral lines produced by doubly excited levels in simple ions tend to have energies which form groups slightly below the energies of the characteristic resonance lines of the next higher stage of ionization. Thus lines within such a group are often referred to as "satellites" to the associated resonance lines. However, the simplicity of this satellite structure is lost in complex ions (e.g., moderately stripped, heavy ions).

The direct use of doubly excited levels for population inversion was suggested by Malozzi, et al., on the basis of observations of satellite emissions to the resonance lines in hydrogen-like aluminum ions generated by a very high power  $\text{Nd}^{+3}$ :glass laser.<sup>(15)</sup> Experiments of this type are presently being pursued. To obtain a useful inversion one requires large electron densities in such a scheme. The reason is because most of the ions so excited decay by autoionization before a radiative process can begin, so a large formation rate of excited states is required.

To pick candidate transitions, we would seek doubly excited levels with large cross sections for dielectronic capture, i.e., large cross sections for autoionization, as well as having large radiative cross sections. Such levels can be found but a problem often arises. The radiative processes are usually found on transitions either to the lowest lying shell vacancy of the ion or to another excited state with a large cross section for dielectronic capture. The rapid filling of the lower level means in such cases the inversions, if they can be attained, will be very short lived. Further work on this scheme may be

fruitful, however, since we presently have reliable cross section data for only a very limited number of doubly excited levels on a rather limited list of ions.

Whether or not dielectronic recombination leads directly to the formation of an upper laser level, cascade decay from doubly excited states may be an effective laser pumping mechanism. For example, when one of the two excited electrons decays to the lowest available shell vacancy, a singly excited ion remains. The formation rate of this singly excited level may be rather different than would be true for direct collisional excitation. Thus the level population could be made larger by this mechanism than on other levels accessible only by direct excitation.

Jaegle and coworkers have interpreted certain line emissions from a laser-produced, two plasma experiment as caused by inverted populations.<sup>(14)</sup> The excited state formation is interpreted as occurring by cascade from autoionizing levels.<sup>(16)</sup> Their gain observation has yet to be confirmed in other laboratories, but this work shows that cascades from autoionizing levels make important contributions to laser plasma emission spectra and thus can be an important level pumping mechanism.

Whether employed directly or indirectly as a pumping mechanism dielectronic recombination is most important at high electron densities and moderate temperatures. These are present in region II of Fig.2. Depending on the atomic weight of the target atoms the highest stages of ionization may not be present in this region due to the electron temperature distribution. However, the highest ion particle density is present in this region and the total line radiation due to all exciting processes

may be highest from this region. The combination of high radiation density and high ion density means that in this region it is important to consider optical pumping as a possible inversion mechanism.

Absorption of line radiation modifies excited state populations. It is not easy to find discrete transitions in different ions to be in close coincidence, and more difficult still to find a pair of such ions which might be found to coexist under a given set of laser plasma conditions. Therefore, in their proposal Peacock and Norton point out that in a high density plasma, radiation trapping may cause resonance line profiles to exhibit a significantly larger half width due to saturation effects near line center.<sup>(17)</sup> This effect is sometimes referred to as opacity broadening. These larger effective linewidths can reduce the stringent requirements for energetic coincidence between transitions. Radiation trapping effects require careful analysis because some of the trapped radiation may be lost at high electron densities due to collisional destruction of the excited state.

Norton and Peacock propose using radiation from the 2p $\rightarrow$ 1s transition in hydrogen-like carbon to pump the n=4 levels from the ground state of the helium-like carbon ion. This may yield an inversion of population on the 4d $\rightarrow$ 2p transition at 186.7 $\text{\AA}$  for a minimum laser power density of  $3 \times 10^{12} \text{ W/cm}^2$  on a specially constructed target. The use of hydrogen-like and helium-like ions is an advantage since these two ion stages may be made to coexist in laser plasmas for a variety of target materials. Such a scheme also has the advantage of permitting quasi-cw operation since the lower laser level can be a short-lived resonance level of the pumped ion, as in the above example.

All of the possibilities mentioned up to now have drawn on the laser plasma environment because high particle temperatures and densities can be achieved on short time scales using laser irradiation. However, the end product of a laser plasma is a moderately energetic stream of ions which preliminary experimental tests indicate can be distributed over a narrow range of angles relative to the target surface normal when the plasma expands into hard vacuum.<sup>(32)</sup> By expanding this stream of ions into a neutral gas background instead, charge exchange reactions may be favored which tend to selectively populate excited levels of ion stages formed by the addition of one electron to the original plasma ions (obtained from the background gas).

In the preliminary calculations, Elton, et al., have found promising combinations using hydrogen or helium as the background gas and using hydrogen-like and helium-like ions from light element laser plasmas.<sup>(12)</sup> Selective pickup into the 3s shell of the ions seems possible for laser plasma expansion energies with inversions produced on 3s $\rightarrow$ 2p transitions in the extreme vacuum ultraviolet.

### III. MEASUREMENT OF LASER PLASMA CONDITIONS

The preceding discussion of excited state production and laser pumping schemes has been highly qualitative. It is hoped that the reader will seek out the more quantitative discussions in the indicated references. However, no matter how reliably we may be able to calculate the rates of excited state production, the usefulness of the calculation ultimately hinges on the accuracy with which we know the plasma conditions. To make reliable gain estimates, we must specify the local particle densities and temperatures, the transition linewidths in the region of interest and, possibly, the ion expansion velocities. It is the purpose of this section to indicate how such information may be obtained in a quantitative manner from a laser plasma experiment.

Two kinds of measurements are available to an experimenter which are non-perturbing. First, there are measurements of the particle spectrum of the freely expanding plasma, including the electron and ion energy<sup>(18)</sup> distribution, total ion currents,<sup>(19)</sup> the ion charge state distribution<sup>(18)</sup> and, possibly, a neutron current and spectrum. Second, there is the measurement of the electromagnetic radiation from the plasma, including optical,<sup>(19)</sup> ultraviolet, and soft x-ray emission.<sup>(20,21)</sup>

We will concentrate our discussion on the techniques using extreme VUV and soft x-ray radiation to diagnose the laser plasma. (The other techniques are referred to and described in volume 3.)

This VUV and soft x-ray instrumentation is a natural ingredient in a soft x-ray laser experiment. We thus hope to emphasize the versatility of measurements made in this part of the spectrum.

The assignment of values to plasma parameters from spectral measurements requires an appropriate model of the relevant physical processes in the plasma. One may choose to use an analytic or a numerical approach to this assignment. To make an analytic model tractable, a number of simplifying assumptions must be made. In return for this one can readily predict the trends implied by a systematic variation of experimental conditions. Ultimately, however, a numerical model is needed to build a detailed knowledge of laser plasma conditions. In what follows we will review the use of some simple analytic models for deducing electron temperature and density in a plasma and apply them to a sample experimental spectrum obtained from a laser produced plasma. We will then discuss some of the weaknesses in the analytic models and briefly describe the use of numerical modeling techniques.

We will begin by discussing the spectral signatures of particle temperatures with primary emphasis on electron temperature. We will assume for the present that we are investigating a plasma of uniform temperature and density and reserve the spatial resolution of the information for later discussion. We will also assume that the electron velocity distribution is (locally) approximately Maxwellian. We might hope that this would be true for even moderately short laser heating pulses, say, 50psec. FWHM and electron densities of  $10^{20} \text{ cm}^{-3}$  or so. (From eq. 1 with  $kT_e = 1 \text{ Kev}$ ,  $n_e = 10^{20} \text{ cm}^{-3}$  we have  $\tau_{ee} = 10^{-11} \text{ sec.}$ )

The emission from a laser heated plasma consists of both line and continuum components in the soft x-ray region. The detailed distribution of both components is sensitive to the electron temperature. We will first consider the distribution of the continuum.

Continuum radiation is produced by bremsstrahlung (free-free) and recombination (free-bound) processes. The bremsstrahlung emission coefficient is given by<sup>(5)</sup>

$$\epsilon_v^{ff} = 1.36 \times 10^{-41} \left[ \frac{\chi_h}{kT_e} \right]^{1/2} \sum_z z^2 n_{iz} n_e g_{ff} \exp(-hv/kT_e) \text{ ergs/cm}^3 \text{ sr} \quad (4)$$

while recombination emission coefficient is given (for hydrogenic ions) by<sup>(5)</sup>

$$\epsilon_v^{fb} = 1.36 \times 10^{-41} \left[ \frac{\chi_h}{kT_e} \right]^{3/2} n_e \sum_z \sum_n \frac{2z^4}{n^3} n_{iz} g_{fb} \exp \left[ \frac{z^2 \chi_h}{n^2 kT_e} - \frac{hv}{kT_e} \right] \text{ ergs/cm}^3 \text{ sr} \quad (5)$$

where  $\chi_h$  is the ionization potential of hydrogen  
 $ze$  is the ionic charge  
 $n_{iz}$  is the population of ions of charge  $ze$   
 $n_e$  is the electron density  
 $n$  is the principal quantum level of a recombination transition.  
 $g_{ff}, g_{fb}$  are Gaunt factors for free-free and free-bound transitions, respectively.

These expressions are valid when  $hv \gg kT_e$ , i.e., when looking at the high energy tail of the spectrum. While one process or the other may predominate for various plasma temperatures and ionic compositions, if one examines the radiation at sufficiently high frequency the same spectral dependence will be observed. The observation can be simply accomplished by fitting a broadband detector with a high pass filter, the latter which is conveniently made using thin metallic foils. The transmission of a foil is simply  $e^{-k_v t}$

where  $k_v$  is spectral mass absorption coefficient and  $t$  is the foil thickness. If identical (or suitably normalized) detectors are fitted with foils of different thickness and if the low frequency cutoff of the foil is high enough to make the transmitted spectral distribution proportional to  $e^{-hv/kT_e}$  then the relative transmission through each foil is given by

$$R = \frac{\int_0^{\infty} e^{-hv/kT_e} e^{-k_v t} dv}{\int_0^{\infty} e^{-hv/kT_e} dv}.$$

Elton has computed this ratio for various values of  $T_e$ ,  $k_v$ , and  $t$  and this published data is commonly used, within its limitations, to estimate laser plasma electron temperatures. An example of a series of curves for various temperatures with aluminum foils is shown in Fig. 5.

With moderate-to-high Z plasmas, line emission can easily fall within the transmission window of convenient foils and upset the validity of the above measurement techniques. However, in these cases the line emission itself may be used to estimate the electron temperature if some means for recording a dispersed spectrum is provided. The instrumentation to accomplish this can often be extremely simple as we will see.

Sometimes the mere identification of a prominent series of lines will establish very good limits on the plasma electron temperature. This is due to the fact that the ionization potential does not increase rapidly as electrons are removed from a given shell but does increase greatly as the first electron from a filled shell is removed. If one can record the spectra using a calibrated instrument, then a more refined

estimate of the electron temperature can be obtained. For laser plasma electron temperatures up to 1 Kev and targets of moderate atomic weight, the principal lines from K-shell electrons are usually observed, i.e., the characteristic resonance lines of the helium-like and hydrogen-like ions. If we assume that direct collisional excitation is the chief mechanism for producing this radiation, we could estimate the temperature from the relative intensities of resonance lines of one of the ions. However, we know that recombination processes may be important in exciting higher lying levels of a particular ion, especially at high particle densities. Therefore, when one- and two-electron spectra are present, it is convenient to measure the ratio of intensities of the first resonance line in each series.

The ratio of resonance line intensities from hydrogen-like and helium-like aluminum ions is shown in Fig. 6. Two different assumptions about plasma conditions are accounted for here. In the so-called corona model excited state lifetimes are assumed short compared to collision times, an assumption which should apply at low densities. In the collisional-radiative (CR) model collisional rates may exceed radiative rates for levels with high principal quantum number, an assumption which will apply at high densities. (One consequence of the CR model is the effective lowering of ionization potentials due to contributions from multistep collisional excitation.)

At very high particle densities radiation trapping effects can give misleading estimates of the electron temperature if they are based on line ratio measurements.<sup>(23)</sup> These effects can be accounted for in the temperature measurement but a knowledge of the particle densities is

required. We will next give a brief review of techniques useful in measuring plasma particle densities.

Several techniques are available to measure plasma particle densities. If a detector is available whose absolute soft x-ray sensitivity is known, and if the electron temperature is known, then a knowledge of the source dimensions allows the ion densities to be deduced from line intensity measurements and the electron density to be deduced from the continuum intensity. Unfortunately, while calibrated detectors are available, an accurate knowledge of the dimensions of the radiating region of a laser plasma is seldom available. Thus, other less direct methods are usually employed.

One possibility is to observe Stark broadening of spectral lines and infer the particle density from the average local electric field produced by an appropriate distribution of particles. However, if ion temperatures are high, Doppler broadening may mask the Stark effect. Instead of observing resonance (e.g., Lyman series) lines one can get more pronounced Stark effects by observing excited state (e.g., Balmer series) transitions at longer wavelengths. The emission intensities on these lines are substantially lower than on resonance lines. Moreover, the theory of Stark broadening in plasmas of moderate-to-high Z ions is still poorly developed.<sup>(24)</sup> Thus only a few laser plasma density measurements using Stark profiles have been reported.<sup>(25)</sup>

A density estimate can be made from the Stark effect in some cases without a profile analysis. Noting that the energy levels of high principal quantum number are progressively closer together, then at a given particle density there will be some level at which the Stark

broadening equals the separation to the next higher level. This level, from which discrete line emission is last observable, is said to lie at the Ingliess-Teller limit for the series.<sup>(26)</sup> The identification of this level in hydrogen plasmas is one of the oldest methods for measuring plasma particle densities.<sup>(27)</sup>

To obtain a density estimate in either case, one must calculate the electric microfield distribution seen by a typical ion in the plasma. This calculation is facilitated by the assumption that the plasma particles are essentially stationary during the radiative lifetime of the excited state of interest. However, calculations have been carried out only for the case of singly-charged plasma ions. Ion correlation corrections have only been computed for cases where the Debye length is larger than the interparticle distance. For high-Z ions a satisfactory theory is still under development so that observations of line broadening effects in laser plasma emission must be analyzed with caution.

Another feature of the line emission which can yield density information is the intensity ratio of certain lines. In atoms where a forbidden transition is energetically close to an allowed transition, the intensity of the former is determined by the importance of electron collisional quenching of the level. The intensity ratio of these two lines will depend on the electron density over a certain range.

We may identify the ranges of behavior bounded by  $t_a$  and  $t_f$ , the lifetimes of the allowed and metastable levels respectively. If the quenching time is smaller than  $t_a$  then the intensities of the lines is independent of  $n_e$ . If the quenching time is greater than  $t_f$  the intensity of both lines is proportional to  $n_e$ . However, if the quenching time is between  $t_a$  and  $t_f$ , then only the intensity of the allowed transition depends on  $n_e$  and thus the ratio of the lines is proportional to density.

In laser plasma work a most useful pair of lines in this connection is present in the spectra of helium-like ions. These transitions are the resonance line (sometimes identified by the symbol "w"),  $1s2p \ 1P_1 \rightarrow 1s^2 \ 1S_0$ , and the intercombination line (identified as "y"),  $1s2P \ 3P_1 \rightarrow 1s^2 \ 1S_0$ . Radiative and collisional processes for these transitions have been carefully studied and an expression for the ratio given as<sup>(24)</sup>

$$R = \frac{I_w}{I_y} = R_1 + P n_e$$

where  $R_1 = 1.8$  and  $P$  is a coefficient which depends on  $kT_e$  and  $z$ . The ratio is plotted in Fig. 7 as a function of electron density for two temperatures.

It is clear that the use of the intensity ratios of spectral lines to estimate electron temperatures and densities is a somewhat interactive process, i.e., a knowledge of the electron temperature is needed to estimate density and vice versa. Ambiguities in the analysis can be reduced if more than one pair of lines can be used in each case or if other diagnostics (such as observation of the Ingliess-Teller limit) can be used to cross-check the results.

To illustrate the diagnostics problem we will describe and analyze a laser plasma experiment performed in the Laboratory for Laser Energetics at the University of Rochester. The laser system used to heat the plasma is a multistage,  $Nd^{+3}$ :glass laser. It consists of a passively mode-locked Q-switched oscillator, an optical network which selects and transmits a single pulse from the train, and an amplifier system which is decoupled from both internal

feedback and external (e.g., target) reflections. A schematic of the system is given in Fig. 8. With this laser, single pulses with energies up to 20 joules at 100-200 psec. FWHM have been focussed onto solid targets of moderate atomic weights with a 3" diameter f/4 aspheric lens designed and fabricated at the University of Rochester.

Perhaps one of the most difficult parameters to measure in such experiments from the standpoint of the laser system is the diameter of the focal spot of the beam under full power conditions. Aberrations accumulated by the beam on passing through even a moderately large amplifier system such as this one will seriously degrade the focussing properties.<sup>(29)</sup> By examining the angular widths of the x-ray lines emitted from the target we estimate that the heated region of the plasma is approximately 100 $\mu$ m in diameter. This means that focussed intensities of approximately  $10^{15}$  w/cm<sup>2</sup> are produced by this laser system.

Although such a source of x-rays is hardly infinitesimal, it is sufficiently small to permit the use of a slitless, flat crystal type spectrometer to obtain an adequately dispersed soft x-ray spectrum. A schematic diagram of the geometry of such a spectrometer is shown in Fig. 9. By choosing a suitably oriented crystal from the acid phthalate family (e.g., TAP, RAP, etc.) sufficiently high x-ray reflectivity can be obtained to get a good quality spectrum on a single shot. (This is particularly desirable if the laser pulse energy is not highly reproducible from shot to shot.) In our experiment the crystal is located approximately 20cm. from the source. At this distance the angular diameter of the source is larger than the angular width of the rocking curve of the crystal and the spectral resolution is source-size limited.

Figure 10 shows a microdensitometer trace of a portion of a spectrum recorded on Kodak no-screen x-ray film when a 7.9 joule pulse with 100psec. FWHM was focussed onto a solid aluminum target. The principal resonance lines from helium-like and hydrogen-like aluminum ions are quite pronounced. Moreover, satellite lines from doubly excited levels in lithium-like and helium-like ions are clearly present, though not fully resolved. Using this spectrum, which is a time- and space-integrated measurement, we will briefly discuss the problem of reducing this data to obtain estimates of plasma electron temperature and density.

Although the recorded spectrum is an integrated measurement, there may be factors at work which tend to localize at least some of the features. Assuming that the spatial distributions illustrated schematically in figure 1 are stationary, then the radiation of lines from a particular ionization stage will be confined to the region characterized by a temperature which just sustains that stage of ionization. The observed lines could thus be localized by a steep temperature gradient, such as shown in region II, Fig. 2. If the temperature is slowly varying, such as shown in region III, Fig. 2, a steep density gradient will tend to weight the strength of the emitted lines toward the high density region, again localizing the emission.

As a first step then it is only necessary to assume that the distributions represented in figure 1 are stationary over the major portion of the laser heating pulse. This assumption must be tested over a variety of conditions, especially including the width of the heating pulse. Such tests are being undertaken in several laboratories

using high speed electrooptic streak cameras to photograph the plasma motions. Elaborate numerical simulations of the plasma evolution are also being used to improve our understanding of these processes. Our own such simulations suggest that under the conditions of the present experiment that the plasma motion is slight over the major portion of radiative activity. We will discuss the data in Fig. 10 from the standpoint of a localized emission region.

To convert the recorded optical density into irradiance, we performed a calibration of the H vs. D curve for no-screen film over the range of soft x-ray wavelengths in Fig. 10. We find that it is important to do this under conditions representing actual usage rather than relying on published data produced, in all likelihood, under different conditions.

Taking the intensity ratio of the helium-like resonance line ( $w$ ) to the hydrogen-like resonance line ( $L_{\alpha}$ ) gives an electron temperature of 530 eV using the CR model as shown in Fig. 6. Recalling that this calculation assumes an optically thin medium, we can check our result using the intensities of the satellite lines labeled j, k in Fig. 10. Gabriel has given a formula for the expected ratio of intensities between the satellites j, k and the resonance line w as a function of temperature.<sup>(30)</sup> Using this we find that the observed intensity of w is 92% of the value expected at a temperature of 530 eV. Since the plasma should be optically thin to the satellite radiation (the lower level is an excited state) and since the resonance line w should be the most seriously affected by opacity, we conclude that this electron temperature characterizes the radiating region in this experiment.

It is interesting to note that if one attempts to estimate the temperature using the series of intensity ratios of the lines from the helium-like sequence only, progressively higher temperatures are predicted by the corona model. This directly shows that neglecting multistep excitation of high lying levels is not justified.

To estimate the particle density we can compare the ratio of intensities of the helium-like intercombination line (*y*) to the resonance line (*w*) in Fig. 10. In this case the estimate will be subject to uncertainties due to the fact that the intercombination line is not well resolved from the resonance line. Using an expanded scale plot of the data in Fig. 10 we can estimate a contribution to the *x,y* feature from the wings of *w* assuming a symmetric line shape. The intensity ratio is determined and compared to the plot in Fig. 7. We obtain an electron density estimate of  $1.5 \times 10^{20} \text{ cm}^{-3}$ .

It should be pointed out that this estimate is a lower bound since there may be other contributions to the spectral feature label *x,y*. While the magnetic dipole transition,  $1s2p \ 3P_2 \rightarrow 1s^2 \ 1S_0$ , (*x*) probably makes a negligible contribution to this feature, there are two satellite lines between *x*, *y*, and *w*. Any allowance made for their intensity will, of course, raise the estimated electron density. Because of the various uncertainties, it would be desireable to have slightly better spectral resolution upon which to base this kind of estimate.

From Fig. 10 it is clear that the principal series lines do not extend to arbitrarily high quantum levels and thus the Inglis-Teller relation

$$n_e = \frac{z^4}{120a_0^3} z^{3/2} n_m^{7.5} \quad (6)$$

may be applied, where  $a_0$  is the Bohr radius and  $n_m$  is the principal quantum number of the last discernable line in the series. In both the helium-like series ( $A_1^{+11}$ ) and hydrogen-like series ( $A_1^{+12}$ ) the last discernable line appears to be  $n_m=6$ . This gives a density of  $N=4.8 \times 10^{21}$  from the helium-like series and  $N=6.6 \times 10^{21}$  from the hydrogen-like series.

The density estimate computed here from observing the disappearance of principal series lines is an upper limit since instrumental effects could mask the presence of higher lying lines. However, when combined with the lower limit supplied by line ratio analysis, it appears that the observed spectrum is radiated most strongly from the region in the vicinity of critical density,  $n_e = 10^{21} \text{ cm}^{-3}$ . These results are in fairly good agreement with the conditions diagrammed in region II, Fig. 2.

In the above analysis we have chosen to use simple analytic models for the purpose of illustration. Ultimately, it must be recognized that such analysis is incapable of dealing with several aspects of the emission from laser plasmas. For example, an important assumption in these models is the existence of steady state conditions in the plasma. In particular, the electron temperature is assumed to vary in time slowly enough so that the degree and level of ionization of the plasma has the steady state value. For the short laser pulses ( $< 10^{-10}$  sec FWHM) used in many present experiments this assumption is probably unrealistic.

To improve our knowledge of the plasma conditions, we must combine the use of elaborate numerical simulations of the plasma conditions with time-resolved studies of the soft x-ray emission. Presently x-ray streak cameras are under development in several laboratories and such time resolved emission studies will constitute one of their principal applications.

Although simple spectrometers such as shown in Fig. 9 provide useful information, the recorded spectrum is spatially integrated. We thus cannot obtain a direct comparison with the profiles shown in Fig. 2, for example. We have indicated that the radiating region which gives a spectrum such as shown in Fig. 10 may be localized by various weighting factors. As a result x-ray pinhole cameras and spatially dispersing x-ray spectrometers are being employed in current experiments to image the plasma. The use of such instruments, combined with one and two-dimensional numerical plasma simulations should provide the detailed understanding which will permit the design or optimization of conditions for producing inverted populations on soft x-ray transitions.

#### IV. DESIGN OF X-RAY LASER EXPERIMENTS

We will now try to give, in general terms, considerations to be taken in designing an experiment to demonstrate the presence of gain in a laser plasma at soft x-ray and extreme VUV wavelengths. Historically it seems that lasers at optical wavelengths were more often discovered than deliberately invented; this may also turn out to be true with x-ray lasers. However, the worker at optical wavelengths has several advantages to discovery not shared by workers at very short wavelengths. First, we cannot ignore the very important advantage of being able to see the emitted radiation, which greatly facilitates the decision making process and allows many possibilities to be explored quickly. Secondly, the use of regenerative feedback permits weakly amplifying systems to oscillate strongly. In this case successful operation can often be demonstrated with a system which is far from optimized.

If one is to have a reasonable chance to verify gain at very short wavelengths one had best not concede too many more points! Therefore, one should probably narrow the search of the promising proposals to either quasi cw schemes or to schemes in which the gain is likely to survive over most or all of the duration of the incident laser heating pulse. This will enable the diagnostic signal, in whatever form, to be dominated by amplifying effects. Since few high power lasers are presently in operation which produce pulses shorter than 20psec., this requirement appears to rule out easy detection of all self-terminating x-ray laser schemes in the near future. Since cw or quasi cw operation requires rapid decay of the lower laser level we are clearly looking for inversions on excited state transitions. This determines some crude limit on the expected laser transition energy, given the presently achievable laser plasma electron temperatures. The experimental results discussed in the previous

section seem to be representative of achievable conditions and imply excited state transition energies of no more than a few hundred electron volts. Thus extreme VUV instrumentation appears to be essential in present short wavelength laser development efforts.

The lack of available regenerative feedback schemes at these wavelengths means that great care will be required to verify the existence of amplification effects. Direct single pass measurements of gain might be attempted using two laser produced plasmas, one serving as a radiation source for the other to amplify. Such experiments have been criticized as lacking straightforward interpretations but in any event are incapable of being as sensitive as a multipass, i.e., regenerative experiment.

The difficulty is further compounded by the fact that overall laser plasma dimensions are small. This means that a high gain coefficient may translate into a small overall amplification factor. While it is practical to irradiate long, filamentary shaped plasmas using cylinder lenses, the transverse dimension of the focal line is still limited by laser beam aberrations in most systems. Thus the focal area of such a system will be large. This reduces the specific focal plane intensity which will limit the plasma temperature and thus the ionization stages achieved. It seems adviseable to recommend maximum plasma lengths between 0.1 and 1.0cm. using presently available lasers.

Given such a length constraint we would feel obliged to seek a minimum gain coefficient between 1.0 and  $10.0\text{cm}^{-1}$  to achieve a readily measureable effect. This is very high by conventional laser standards and suggests that special care should be taken to minimize gain degrading

effects such as Doppler broadening of the plasma ions. It seems wise to plan on two step excitation in many experiments. The first step will involve the creation of a plasma in the desired stage of ionization. This could be accomplished without the need for a very short pulse laser. After an interval sufficient to permit the ion temperatures to drop, a second, short pulse may be used to heat the plasma electrons. If this pulse is short compared to the time scale given in equation 2, then the excitation may take place while keeping the ion temperature and thus the Doppler widths low.

If the proposed scheme to be tested appears to work best over a limited range of particle density, it should be kept in mind that the experimenter can control the deposition point of the focussed laser pulse by appropriately choosing the laser wavelength. Since high power lasers are available at only a few wavelengths, efficient frequency conversion schemes may have to be employed. In a two step excitation scheme, the two laser pulses may be chosen at different wavelengths for the best effect.

It may be observed that among presently available discharge excited lasers many of the highest gain systems are of the self-terminating variety. Using a cleverly designed two step excitation scheme, it may be possible to overcome our objection to self-terminating systems. In one proposal, for example, a line focus plasma is created by a tailored Q-switched laser pulse.<sup>(31)</sup> Excitation is then accomplished by focussing a second, ultrashort (mode-locked) laser pulse along the axis of the plasma. The duration of the excitation pulse may be short compared to the transit time of the plasma and thus a travelling wave pumping scheme is effected.

Assuming that gain has been achieved in a laser plasma, we must ask what constitutes convincing evidence of the achievement? The lack of regenerative feedback means that we are denied the observation of a sharply defined threshold effect; this has proved to be a sticky point for experimenters to date. Short of a direct, single pass gain measurement in a plasma we may look for an excitation dependent directionality of the radiation from the particular transition of interest when excited in a filamentary geometry. If the upper laser level were also the upper level of a non-inverted transition (e.g., a resonance transition) then a comparison of the different directional properties of the two transitions would increase certainty. Evidence of line narrowing might be sought if sufficiently high spectral resolution is available. However, all such evidence is ideally acquired on a single shot basis and this often poses a problem in light gathering power.

Less direct but still acceptable evidence of gain might be developed from measurements of level populations. These may be conveniently measured by the strengths of lines emitted from the levels of interest. However, the oscillator strengths and/or transition probabilities must be well known to do this and this is usually true only for resonance lines in the case of highly charged ions. Thus, the conditions on many potentially amplifying transitions may be inaccessible by this method.

In spite of the difficulties associated with the method, we have a preference for the observation of directional effects as an ultimate diagnostic. This stems from the belief that applications for such a light source will ultimately develop from a filamentary geometry of the medium. The observation of a useful effect in this geometry thus hastens the development of these applications.

## V. SUMMARY AND CONCLUSION

It was the purpose of this paper to examine the conditions present in a laser produced plasma and to discuss their suitability for providing soft x-ray amplification. A variety of representative proposals were outlined, each of which attempts to exploit different features and regions of the plasma to obtain inverted populations. The problem of designing an experiment to demonstrate gain is twofold. The first is to measure and match the actual plasma conditions to the choice of laser pulse time history, target composition and geometry. The second is to produce a convincing diagnostic for enhanced stimulated emission in the absence of regenerative feedback. In most current experiments the measurement of plasma conditions is emphasized. It appears that more work can usefully be applied to the problem of gain diagnosis.

The development of soft x-ray laser action will undoubtedly stimulate considerable development in x-ray materials and recording technology. Whether effective methods for regenerative feedback are developed from this may not limit the applications for lasers in this wavelength range, however. In particular, the generation of coherent energy by nonlinear optical techniques is presently being extended into the extreme vacuum ultraviolet.<sup>(33)</sup> The use of such techniques with a soft x-ray amplifier<sup>(31)</sup> could hasten many exciting applications<sup>(34)</sup> for a source of high power, coherent x-rays.

### REFERENCES

1. A. Javan, W.R. Bennett, Jr. and D.R. Herriott, Phys. Rev. Lett. 6, 106 (1961).
2. M.J. Bernstein and G.G. Comisar, J. Appl. Phys. 41, 729 (1970).
3. I.N. Knyazev and V.S. Letokhov, Opt. Comm. 3, 332 (1971).
4. L. Spitzer, Physics of Fully Ionized Gases, Interscience (New York, 1967).
5. H.R. Griem, Plasma Spectroscopy, (McGraw-Hill, New York, 1964).
6. L.I. Gudzenko and L.A. Shelepin, JETP 18, 998 (1964),  
also, L.I. Gudzenko and L.A. Shelepin, soviet Phys. Doklady 10, 147 (1965).
7. W.L. Bohn, Appl. Phys. Lett. 24, 15 (1974).
8. K.G. Whitney and J. Davis, J. Appl. Phys. 45, 5294 (1974).
9. T.C. Bristow, M.J. Lubin, J.M. Forsyth, E.B. Goldman, and J. Soures, Opt. Comm. 5, 315 (1972).
10. R.C. Elton, Appl. Optics 14, 97 (1975).
11. W.W. Jones and A.W. Ali, NRL Memorandum Report 2999, U.S. Naval Research Laboratory, 1975; also A.W. Ali and W.W. Jones, NRL Memorandum Report 3015, U.S. Naval Research Laboratory, 1975.
12. R.A. Andrews, R.C. Elton, J. Reinjes, R.C. Eckardt, R.H. Lehmberg, R. Waynant, T.N. Lee, L.J. Palumbo, J.M. McMahon, D. Nagel, and W. Jones, NRL Memorandum Report 2910, U.S. Naval Research Laboratory, 1974.
13. F.E. Irons and N.J. Peacock, J. Phys. B 7, 441 (1974).
14. P. Jaegle, A. Carillon, P. Dhez, G. Hamelot, A. Sureau and M. Cukier, Phys. Lett. 36A, 167 (1971).

15. P.J. Mallozzi, H.M. Epstein, R.G. Jung, D.C. Appelbaum, B.P. Fairand, W.J. Gallagher, and B.E. Campbell, Paper presented at VIII International Conference on Quantum Electronics (Post-deadline Paper), San Francisco, 1974.
16. A. Carillon, G. Jamelot, A. Sureau, and P. Jaegle, Phys. Lett. 38A, 91 (1971).
17. B.A. Norton and N.J. Peacock, J. Phys. B 8, 939 (1975).
18. M. Oron and Y. Paiss, Rev. Sci. Inst. 44, 1293 (1973).
19. J. Soures, L.M. Goldman and M. Lubin, Nuclear Fusion 13, 6 (1973).
20. P.J. Mallozzi, H.M. Epstein, R.G. Jung, D.C. Applebaum, B.P. Fairand, and W.J. Gallagher, in Fundamentals of Applied Laser Physics, edited by M.S. Feld, A. Javan, and N.A. Kurnir, (Wiley Interscience, New York, 1973) pp. 165-220.
21. D.J. Nagel, P.G. Burkhalter, C.M. Dozier, J.F. Holzrichter, B.M. Klein, J.M. McMahon, J.A. Stamper and R.R. Whitlock, Phys. Rev. Lett. 33, 743 (1974).
22. R.C. Elton, NRL Memorandum Report 6738, U.S. Naval Research Laboratory, 1968.
23. A.G. Hearn, Proc. Phys. Soc. 81, 648 (1963).
24. H.R. Griem, Spectral Line Broadening by Plasmas, Academic Press, New York (1974).
25. M. Galanti, N.J. Peacock, B.A. Norton and J. Puric, Proc. Fifth IAEA Plasma-Fusion Conf., Tokyo (1974).
26. C.R. Vidal, J. Quant. Spectrosc. Radiation Transfer 6, 461 (1966).
27. D. Inglis and E. Teller, Astrophys. J. 90, 439 (1939).
28. H.J. Kunze, A.H. Gabriel and H.R. Griem, Phys. Fluids 11, 662 (1968).
29. E. Bliss, G. Sommargren, H.J. Weaver, D.R. Speck, J. Holzrichter, J. Erkkila and A. Gross, Laser Program Annual Report, Lawrence Livermore Laboratory, 1974, pp. 191-197.

30. A.H. Gabriel, Mon. not. R. Astr. Soc. 160, 99 (1972).
31. R.A. Andrews, R.C. Elton, J. Reintjes, T. Lee and R. Eckardt, NRL Memorandum Report 3057, U.S. Naval Research Laboratory, 1975.
32. Yu A. Bykovskii, Yu P. Kozyrev, S.M. Silnov, and B. Yu Sharkov, Sov. J. Quantum Electron. 4, 405 (1974).
33. D. M. Bloom, G.W. Bekkers, J.F. Young and S.E. Harris, Applied Phys. Lett. 26, 687 (1975); see also A.H. Kung, J.F. Young and S.E. Harris, Appl. Phys. Lett. 22, 301 (1973).
34. G.C. Bjorklund, S.E. Harris and J.F. Young, Appl. Phys. Lett. 25, 451 (1974).

## FIGURE CAPTIONS

Fig. 1 The early evolution of a plasma produced by irradiation of a solid surface by a very high power laser pulse. In (a) the solid surface is shown prior to irradiation. As the laser pulse is incident a narrow region of ionized particles forms near the surface as in (b). Absorption of energy continues and a hot plasma is formed with approximately the density profile shown in (c).

Fig. 2 Representative electron temperature and density profiles in a neodymium laser plasma. The abscissa measures the distance from the solid surface in microns. The four regions indicated are discussed in the text.

Fig. 3 Energy level diagram for proposed population inversion in helium-like oxygen.

Fig. 4 Energy level diagram for proposed population inversion in carbon-like ions.

Fig. 5 Relative transmission coefficient of thin aluminum foils for bremsstrahlung x-rays produced at various temperatures.

Fig. 6 Predicted line intensity ratio of the hydrogen-like resonance line ( $L_{\alpha}$ ) to the helium-like resonance line ( $w$ ) in an aluminum plasma. The predictions of both the corona and collisional radiative (CR) models are shown.

Fig. 7 Predicted line intensity ratio of the helium-like resonance line ( $w$ ) to intercombination line ( $y$ ) as a function of electron density in an aluminum plasma at two temperatures.

Fig. 8 Schematic diagram of a multi-stage Nd<sup>+3</sup>:glass laser system used in laser plasma x-ray experiments at the University of Rochester.

Fig. 9 Simple crystal spectrometer used in laser plasma experiments.

Fig. 10 Microdensitometer trace of the spectrum of an aluminum plasma produced by a focussed, 7.9 joule, 10<sup>-10</sup> sec. pulse from the laser shown in Fig. 7. The spectrum was recorded on the instrument shown in Fig. 8.

TABLE 1

<u>SYSTEM</u>	<u>ION</u>	<u>TRANSITION</u>	<u>WAVELENGTH</u>	<u>LIFETIME, SEC.</u>
He-Ne Laser	Ne	5s $\rightarrow$ 3p	6328 $\text{\AA}$	$10^{-8}$
Ar-Ion Laser	Ar $^+$	4p $\rightarrow$ 4s	4880 $\text{\AA}$	$10^{-8}$
Laser Plasma	O $^{+6}$	3p $\rightarrow$ 2s	128 $\text{\AA}$	$10^{-11}$
Laser Plasma	Al $^{+12}$	2p $\rightarrow$ 1s	7.17 $\text{\AA}$	$10^{-12}$

Approximate excited state lifetimes for visible laser transition and representative soft x-ray transitions in laser produced plasmas.

TABLE 2

System	Plasma	T <sub>e</sub> , ev	n <sub>e</sub> , cm <sup>-3</sup>	$\tau_{ee}$ , sec.	$\tau_{ei}$ , sec.
He-Ne Laser	He $^+$	0.5	$3 \times 10^{11}$	$10^{-4}$	$10^{-2}$
CO <sub>2</sub> Laser (atm.)	He $^+$	4.0	$10^{13}$	$10^{-6}$	$10^{-4}$
Ar-Ion Laser	Ar $^+$	3.0	$10^{14}$	$10^{-7}$	$10^{-5}$
CO <sub>2</sub> Laser Plasma	Al $^{+13}$	$10^3$	$10^{19}$	$10^{-10}$	$10^{-8}$
Nd Laser Plasma	Al $^{+13}$	$10^3$	$10^{21}$	$10^{-12}$	$10^{-10}$

Approximate electron and electron-ion thermalization times predicted by equations 1 and 2 for representative electric discharge lasers and laser-produced plasmas.

TABLE 3

System	Ion	Transition	Wavelength	$\Delta\nu, \text{Hz}$	$\Delta\nu/\nu$
He-Ne Laser	Ne	5s $\rightarrow$ 3p	6328 $\text{\AA}$	$10^9$	$10^{-6}$
Ar-Ion Laser	Ar $^+$	4p $\rightarrow$ 4s	4880 $\text{\AA}$	$10^{10}$	$10^{-5}$
CO <sub>2</sub> Laser (atm)	CO <sub>2</sub>	00 <sup>0</sup> 1 $\rightarrow$ 10 <sup>0</sup> 0	10.6 $\mu$	$10^9$	$3\times 10^{-4}$
Laser Plasma	O $^{+6}$	3p $\rightarrow$ 2s	128 $\text{\AA}$	$10^{14}$	$3\times 10^{-4}$
Laser Plasma	Al $^{+12}$	2p $\rightarrow$ 1s	7.17 $\text{\AA}$	$10^{15}$	$2\times 10^{-4}$

Approximate transition linewidths for representative electric discharge lasers and typical laser-produced plasmas.

